Volar, Intramedullary, and Percutaneous Fixation of Distal Radius Fractures

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Abstract

Background The management of extra-articular distal radius fractures is highly variable, with no clear consensus regarding their optimal management.

Purpose To assess comparatively the biomechanical stability of Kirschner wire (K-wire) fixation, volar plating, and intramedullary nailing for unstable, extra-articular distal radius fractures with both (1) constant and (2) cyclical axial compression, simulating forces experienced during early postoperative rehabilitation.

Methods Twenty-six volar locking plate, intramedullary nail, and K-wire bone-implant constructs were biomechanically assessed using an unstable extra-articular distal radius bone model. Bone implant models were created for each type of construct. Three samples from each construct underwent compressive axial loading until fixation failure. The remaining samples from each construct underwent fatigue testing with a 50-N force for 2,000 cycles followed by repeat compressive axial loading until fixation failure.

Results Axial loading revealed the volar plate was significantly stiffer than the intramedullary nail and K-wire constructs. Both the volar plate and intramedullary nail required greater than 300 N of force for fixation failure, while the K-wire construct failed at less than 150 N. Both the volar plate and intramedullary nail demonstrated less than 1 mm of displacement during cyclic loading, while the K-wire construct displaced greater than 3 mm. Postfatigue testing demonstrated the volar plate was stiffer than the intramedullary nail and K-wire constructs, and both the volar plate and intramedullary nail required greater than 300 N of force for fixation failure while the K-wire construct failed at less than 150 N.

Conclusions Volar plating of unstable extra-articular distal radius fractures is biomechanically stiffer than K-wire and intramedullary fixation. Both the volar plate and intramedullary nail demonstrated the necessary stability and stiffness to maintain anatomic reduction during the postoperative rehabilitation period.

Keywords
► biomechanics
► distal radius
► fracture
► intramedullary

Clinical Relevance Both the volar plate and intramedullary nail demonstrated the necessary biomechanical stability to maintain postoperative reduction in extra-articular distal radius fractures, warranting further clinical comparison.

Distal radius fractures account for ~15% of all extremity fractures and are among the most common orthopaedic injuries.[1] Treatment varies widely depending on the fracture pattern and functional demand of the patient and includes closed reduction and casting, percutaneous pinning, open reduction and internal fixation, and external fixation.[1,2] Many studies have prospectively compared volar locking plates, intramedullary nail fixation, percutaneous fixation,

and external fixation in varying fracture patterns.[3–10] The majority of these studies found equivalent long-term functional outcomes regardless of fixation modality; thus, currently, there is no clear consensus as to which treatment modality is superior.

Volar plating has gained increasing popularity over the past decade due to its lower complication rate in comparison to other fixation systems, ability to tolerate early rehabilitation, and good to excellent postoperative outcomes.[9,11–13] However, volar plating risks complications of its own, such as flexor tendon ruptures, screw penetration of the extensor compartment, and hand stiffness caused by the disruption of the volar soft tissue envelope.[14–17]

Although a majority of distal radius fractures are amenable to volar plate fixation, fractures without articular involvement or substantial metaphyseal comminution may be treated with Kirschner wire (K-wire) fixation. This treatment modality has several potential benefits including decreased operative time, lower operative cost, and less soft tissue destruction; however, it must be used in select patients because radiologic and clinical outcomes have been shown to be inferior compared with volar plating.[18] Additionally, K-wires risks complications of their own, such as pin tract infection, deep infection, and necessitation for prolonged immobilization.[19–21]

Intramedullary fixation has been proposed as an alternative to both volar plating and K-wire fixation, as it may provide stable internal fixation, minimal soft tissue disruption, and comparable functional outcomes[4,7,22,23]. However intramedullary nailing of distal radius fractures is also associated with its own complications, and clear clinical indications for intramedullary nailing and long-term clinical outcomes have yet to be established.[23,24]

The purpose of this study was to assess comparatively the biomechanical stability of K-wire fixation, volar plating, and intramedullary nailing for unstable, extra-articular distal radius fractures with both (1) constant and (2) cyclical axial compression, simulating forces experienced during early postoperative rehabilitation.

Materials and Methods

Specimen Preparation

Twenty-six fourth-generation composite left radii (P/N 3407; Sawbones, Vashon Island, Washington, USA), designed to replicate human cadaveric bone, were used in this study. Previous studies in femur and tibia models have shown similar mechanical properties between composite and cadaveric bone.[25,26] The use of composite bone allowed for consistent screw purchase due to minimization of anatomic and composite variability encountered in true cadaveric models.

Nine composite bones were implanted with three 4.5-inch × 1.6-mm K-wires (P/N A1607–962; American Medical Specialties, Seminole, FL). Two K-wires were directed from the distal end of the radial styloid to the medial cortex, proximal to the fracture zone. The two K-wires were separated by 3 mm in the anterior-posterior plane. A third K-wire was directed from the Lister tubercle to the volar cortex, proximal to the fracture site. A polyurethane drilling fixture was used to provide consistent location and direction of all three inserted K-wires across each specimen (►Fig. 1).

Eight composite bones were implanted with the WRx (Sonoma Orthopedic Products, Buffalo Grove, Illinois, USA) intramedullary device. The implant was inserted into the radial styloid using 3-mm and 5.5-mm curved awls, starting 9 mm proximal to the distal tip and centered on the radial styloid. The device was locked distally using three 2.7-mm cortical screws per the surgical technique guide (►Fig. 1).

Nine composite bones were fitted with the Acu-Loc distal radius volar locking plate (P/N PL-DR50L; Acumed, Hillsboro, OR, USA) per the manufacturer's recommended

Fig. 1 K-wire, volar locking plate, and intramedullary bone-implant constructs.

technique. A total of three nonlocking 3.5-mm cortical screws (P/N CO-31xx; Acumed) were used to fix the plate proximally and four 2.3-mm locking screws (P/N CO-T23xx; Acumed) were used to fix the plate distally per the manufacture's recommendations (►**Fig. 1**).

All specimens were instrumented before osteotomy to ensure consistent and replicable fixation placement. The fixation constructs were then removed and a clinically applicable fracture model was created with a 5-mm-wide circumferential osteotomy 20 mm proximal to the medial edge of the distal articular surface, perpendicular to the long axis of the bone model. Similar cadaveric and composite bone osteotomy models have been previously reported in the literature.[27,28] In addition to the osteotomy, the proximal portion of the bone models were removed 150 mm proximal to the distal end. The proximal end was then potted in 40–50 mm of polyurethane. Potting was performed such that the distal articular surface was horizontal to the polyurethane block. A polyurethane cast of the distal articular surface with a countersink centered at the intersection of the distal articular surface and the axis of the canal was created to ensure symmetric distribution of forces across the articular surface during testing. Without the polyurethane cast, the asymmetric articular surface of the distal radius would preclude symmetric application of the axial force (►**Fig. 2**).

After the bone models were osteotomized and potted in polyurethane proximally, they were reinstrumented using the original holes to restore the natural anatomic alignment. A spacer block was also placed within the osteotomy site to maintain the 5-mm gap and was removed prior to mechanical testing. All specimens were examined with radiographs to ensure appropriate placement of all implant-specimen constructs (►**Fig. 3**).

Mechanical Testing

Testing was performed on an Instron 8872 Axial Tabletop Servohydraulic Dynamic Testing System (Instron, Norwood, MA, USA) with a 1-kN axial load cell (►**Fig. 2**). Two methods were used to test the bone models: constant loading and cyclical loading.

In constant loading, three specimens from each group were loaded in an axial direction at a constant rate of 10 mm/min until collapse of the osteotomy gap or failure of fixation occurred. The force required to compress the fracture gap by 1 mm, 3 mm, and 5 mm (complete collapse) was recorded.

For cyclical loading, five WRx, six Acu-Loc, and six K-wire constructs were preconditioned using a cyclic load of 5 N at a rate of 3 Hz for a total of 10 cycles. Fatigue testing was then conducted for 2,000 cycles with a 50-N load to simulate 6 weeks of wrist motion in the postoperative rehabilitative period.[29,30] Testing was terminated once 2,000 cycles were achieved or if the specimen experienced complete collapse (5 mm) or fixation failure. Maximum displacement due to cyclic loading was determined for each specimen at this point. Lastly, after 2,000 cycles, postfatigue constant loading was performed as previously described. Constant loading was repeated after cyclical loading to assess whether cyclical loading decreased the biomechanical strength of the three constructs due to fatigue.

During cyclical testing, the zero-displacement position was the position at the beginning of preconditioning. The displacement due to preconditioning was then the start point of the fatigue testing. Correspondingly, the displacement due to fatigue testing was the start point for the postfatigue constant-loading testing. The net settling due to preconditioning and fatigue testing was measured by returning the loading crosshead to the 0-N position after the fatigue test. In cases where the net settling was greater than the constant-loading displacement at a given load, the load to displacement was not recorded.

Statistical Analysis

Statistical significance was defined as $P \leq 0.0167$ after a Bonferroni correction was applied given that we tested multiple hypotheses from the same dataset. This correction decreases the probability of potential type I error. P-values were determined using a t-test with a two-tailed distribution, and Cohen's d was used to determine effect size. A post hoc power analysis was calculated for each statistical comparison. Statistical power was defined as $(1- \beta) > 0.8$. For cases in which the power was less than 0.8, no conclusions were drawn.

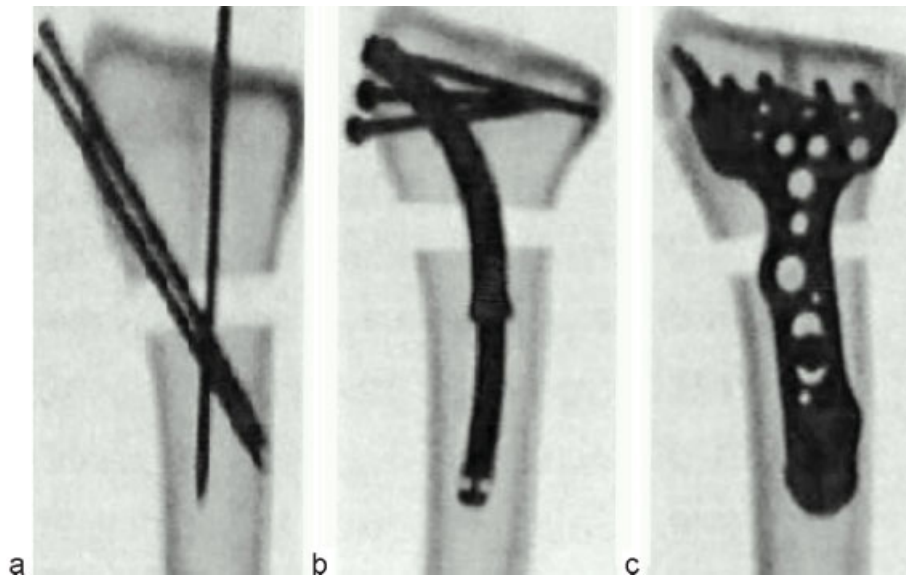**Fig. 2** Test setup of the bone-implant model and polyurethane cast.

Fig. 3 (a–c) Radiographic confirmation of implant positioning.

Results

Constant Loading Results

The force required to displace the fracture by 1 mm, 3 mm, and 5 mm (complete collapse) was measured for all specimens. Complete collapse occurred in all specimens tested. The mean and standard deviation for all specimen groups are reported in ►**Table 1** and ►**Fig. 4**. The compressive loads resisted by the intramedullary nail and volar plate were significantly higher than that for the K-wire model at 1 mm ($p < 0.001$), 3 mm ($p < 0.001$), and 5 mm ($p < 0.001$). The compressive loads resisted by the volar plate were significantly higher than those for the intramedullary nail at 1 mm ($p < 0.014$), 3 mm ($p < 0.001$), and 5 mm ($p < 0.001$).

Cyclical Loading Results

All intramedullary nail and volar plate specimens met the endurance limit goal of 2,000 cycles without collapse. One K-wire specimen collapsed after 139 cycles. This specimen was excluded from postfatigue constant axial compression testing.

All K-wire specimens underwent settling of at least 1 mm, with one specimen settling 3 mm during fatigue testing. The maximum cyclic displacement for the K-wire specimens was significantly higher than that for the intramedullary nail and volar plate specimens ($p < 0.001$) (►**Table 2**). There was no significant difference in maximum cyclic displacement between the intramedullary nail and volar plate specimens ($p = 0.539$) (►**Table 2**). The net settling was significantly higher for the K-wire specimens than for the intramedullary nail ($p = 0.0017$) and volar plate specimens ($p < 0.001$) (►**Table 2**). The intramedullary nail group experienced more net settling than did the volar plate group ($p = 0.0061$) (►**Table 2**).

Collapse of all fractures was again observed in postfatigue constant axial compression testing. The implants all failed in a similar manner to that observed during standard constant-load axial compression testing. The mean and standard deviation for load resisted at 1 mm, 3 mm, and 5 mm of collapse is seen in ►**Table 3** and illustrated in ►**Fig. 5**. Once again, the compressive loads resisted by the K-wire specimens were significantly lower than those for the intramedullary nail and volar plate specimens at 1 mm ($p < 0.001$), 3 mm ($P < 0.001$), and 5 mm ($P < 0.001$). The compressive loads were significantly lower for the intramedullary nail specimens than for the volar plate specimens at 3 mm ($p < 0.001$) and 5 mm ($p < 0.001$). The compressive loads of the intramedullary nail specimens were also lower at

Table 1 Constant-loading axial compression testing for each specimen-implant model at 1 mm, 3 mm, and 5 mm

Description	WRx ($n = 3$)	K-wire ($n = 3$)	Acu-Loc ($n = 3$)
Mean (SD) Load at 1 mm (N)	121.07 (15.77)	13.48 (13.23)	191.62 (24.70)
Mean (SD) Load at 3 mm (N)	208.90 (7.37)	62.06 (14.00)	590.93 (23.41)
Mean (SD) Load at 5 mm (N)	339.88 (16.09)	134.40 (19.17)	813.55 (63.41)

Constant-load axial compression testing for each specimen-implant model at 1 mm, 3 mm, and 5 mm. The compressive loads resisted by the WRx intramedullary nail and Acu-Loc volar plate were significantly higher than those for the K-wire model at 1 mm, 3 mm, and 5 mm ($p < .001$). The compressive loads resisted by the volar plate were significantly higher than for the intramedullary nail models at 1 mm, 3 mm, and 5 mm ($p < 0.05$).
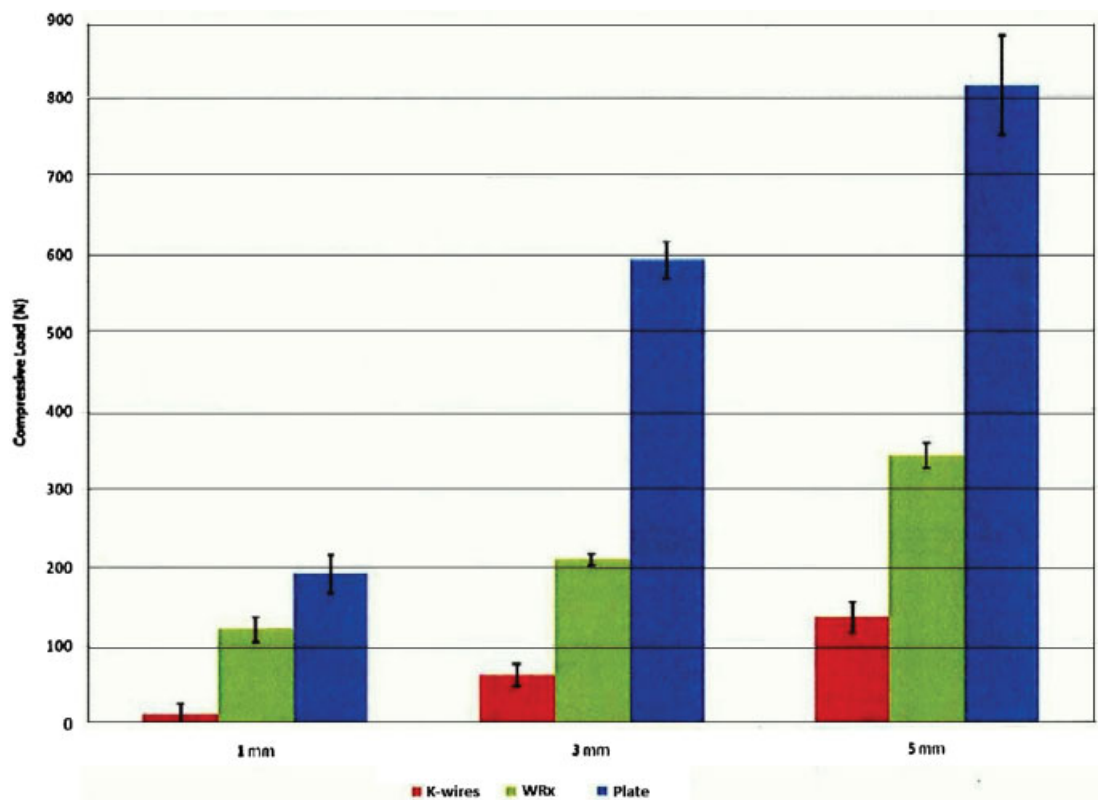
Fig. 4 Average compressive loads of each specimen-implant model resisted during constant-loading axial compression testing.

1 mm compared with the volar plates ($p = 0.037$); however, no conclusion could be drawn, as the power was less than 0.80 (power $= 0.63$).

There was no evidence of implant failure, either pre- or post-fatigue, with constant compression testing. The K-wires showed no permanent deformation, but the construct failed by migration of the implant. The intramedullary nail specimens showed some plastic deformation of the proximal gripping mechanism on plain film but did not exhibit evidence of implant extrusion. This gripping mechanism enables the intramedullary nail to grip the cavity walls, adding stability to the device. The volar plates did not exhibit any deformation with constant compressive testing pre- or post-fatigue, although cracks on the volar cortical surface were observed. The clinical appearance of the specimens following

postfatigue constant compressive axial testing is seen in ►**Fig. 6**.

Discussion

The paradigm for distal radius fracture management continues to evolve, and with the development of more advanced surgical constructs, the indications for operative management of these fractures will likely continue to change. In 1999, 58% of orthopaedic surgeons stated they used K-wire fixation for the surgical stabilization of these fractures, but by 2007 this number decreased to 19%.[31] Important reasons for the decline in popularity of K-wire fixation were the relatively high complication rate and inferior biomechanical and clinical outcomes in comparison to plate fixation.[18,19,32] Over the

Table 2 Maximum displacement and net settling observed during fatigue axial compression testing of each specimen-implant model

Description	WRx ($n = 5$)	K-wire ($n = 5$)	Acu-Loc ($n = 6$)
Mean (SD) maximum cyclic displacement (mm)	0.46 (0.21)	3.13 (0.91)	0.55 (0.249)
Mean (SD) net settling (mm)	0.26 (0.11)	2.83 (1.05)	0.03 (0.032)

Maximum displacement and net settling observed during fatigue axial compression testing of each specimen-implant model. The maximum cyclic displacement at the 50-N cyclic fatigue load for the K-wire specimens was significantly higher than those for the WRx intramedullary nail and Acu-Loc volar plate specimens ($p < 0.001$). There was no significant difference in maximum cyclic displacement between the intramedullary nail specimens and volar plate specimens ($p = 0.539$). The net settling due to the 50-N fatigue load was significantly higher for the K-wire specimens than for the intramedullary nail and volar plate specimens ($p < 0.01$). The net settling was significantly higher in the the intramedullary nail group than in the volar plate group ($p = 0.0061$).

Table 3 Postfatigue constant loading axial compression testing for each specimen-implant model at 1 mm, 3 mm, and 5 mm

| Description	WRx (n = 5)	K-wire (n = 5)	Acu-Loc (n = 6)
Mean (SD) load at 1 mm (N)	108.28 (19.61)	N/A	176.94 (59.36)
Mean (SD) load at 3 mm (N)	190.60 (6.90)	63.43 (42.20)	601.18 (75.52)
Mean (SD) load at 5 mm (N)	314.49 (27.01)	142.32 (36.01)	850.09 (101.62)

Postfatigue constant axial compression testing for each specimen-implant model at 1 mm, 3 mm, and 5 mm. All K-wire constructs experienced settling greater than 1 mm; therefore 1 mm quasistatic axial compressive loads cannot be reported. The compressive loads resisted by the K-wire specimens were significantly lower than the WRx intramedullary nail and Acu-Loc volar plate specimens at 1 mm, 3 mm, and 5 mm ($p < 0.001$). The compressive loads were significantly lower for the intramedullary nail specimens than for the volar plate specimens at 3 mm and 5 mm ($p < 0.001$). The compressive loads of the intramedullary nail specimens were also lower at 1 mm than those of the volar plates ($p < 0.05$); however, no conclusion could be drawn, as the power was less than 0.80.

last decade, volar plating systems have created a great deal of interest in distal radius fracture stabilization, and clinical studies have reported good to excellent outcomes.[8,33–35] However, these plates have not been free of complications, such as tendon damage, tendon rupture, loss of reduction, periosteal stripping, and soft tissue damage.[14,16,36–38] The presence of these complications and limitations of the volar plate have led researchers to pursue alternative means of surgical fixation, and, recently, the intramedullary nail has evolved into clinical practice.[22,39]

Our study aimed to biomechanically compare the constant and cyclical stability of K-wire fixation, locked volar plates, and intramedullary nails in unstable, extra-articular distal radius fractures. We chose to conduct our study using bone

models, which have been previously utilized in similar studies.[11,13,40]

The K-wire specimens were the least rigid among all three constructs tested, and similar results have been previously reported.[32] The Acu-Loc volar plate performed the best in our study, demonstrating greater stiffness and less net settling than the WRx intramedullary nail. These results differ from previous biomechanical studies. Capo et al demonstrated no significant difference in bending stiffness and load to failure between the volar locking plate and intramedullary nail in a cadaveric dorsal comminution fracture model.[41] Similarly, Konstantinidis et al tested multiple volar locking plate designs in addition to a Targon-DR intramedullary nail and demonstrated that the intramedullary nail was equivalent or
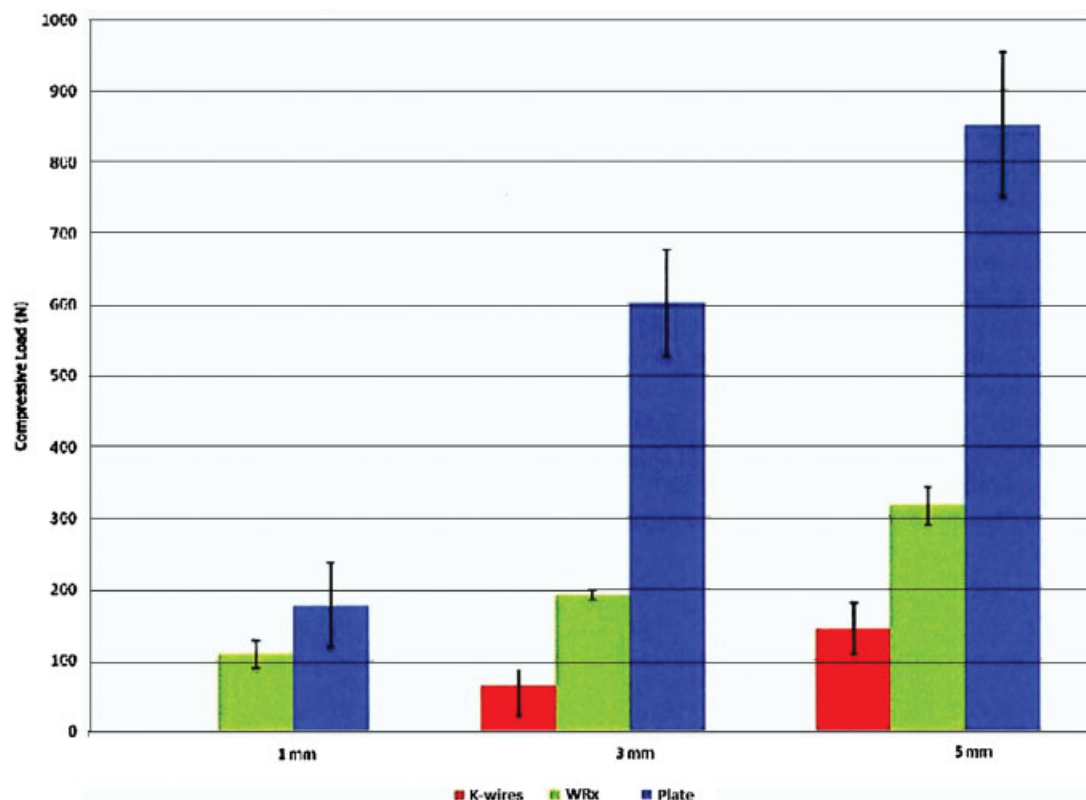
Fig. 5 Average compressive loads of each specimen-implant model resisted during postfatigue constant-loading axial compression testing.
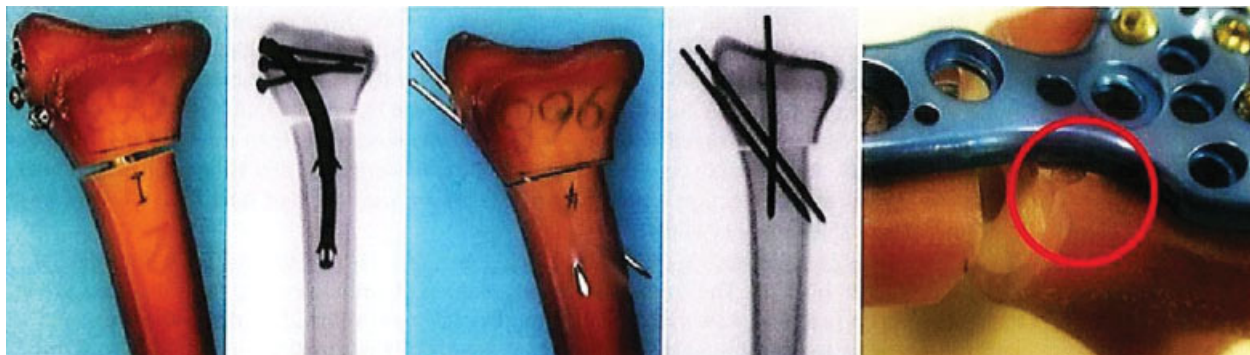
Fig. 6 Photographs and X-rays after constant-loading compression testing. The red circle outlines cracking of the volar cortex on the plate specimens.

superior in bending stiffness and load to failure in comparison to all volar plating systems tested in an unstable dorsal wedge fracture model.[11] Lastly, Kampen et al also demonstrated equivalent stiffness when comparing a unique intramedullary scaffold implant to a DePuy volar locking plate in a fracture model similar to our study.[27]

Although the Acu-Loc volar plating system used in our study was statistically superior to the WRx construct, it is unclear how clinically relevant this may be. Both the volar plate and intramedullary nail required greater than 250 N to achieve complete collapse in constant axial compression testing, and both displayed minimal net settling and displacement during cyclic testing. Previous studies have suggested that the distal radius experiences forces less than 250 N with light activity in the postoperative rehabilitative period, and the ability of the intramedullary nail to withstand forces experienced during postsurgical rehabilitation was demonstrated in our study and previous radiographic and clinical studies.[13,23,42–46]

As the operative management of distal radius fractures has continued to advance, there still remains a subset of fractures that do not necessitate formal open reduction and internal fixation. Percutaneous K-wire fixation may be indicated in extra-articular fractures without metaphyseal comminution in functionally low-demand patients or in patients where operative time needs to be minimized. However, K-wire constructs are associated with inferior clinical outcomes as they often lack the stability necessary to enable early range of motion, as seen in our study.[18] Volar plating may offer the greatest stability but also requires the most dissection of the three constructs tested. The WRx intramedullary device may offer a compromise, offering greater stability than obtained with K-wire constructs by providing immediate bony stabilization as a load-sharing device, while allowing for less invasive insertion than for the volar plate. These theoretical benefits of the intramedullary nail have been partly substantiated clinically. Safi et al demonstrated superior range of motion and Disabilities of the Arm, Shoulder and Hand (DASH) scores for the intramedullary nail than for volar plating at 6 weeks postoperatively.[47] However, this study and two other studies noted no long-term clinical or radiographic differences.[4,7,47]

To date, the intramedullary nail has theoretical and partially proven benefits over other fixation systems, but its use has not been met with widespread enthusiasm, as implantation of a rigid nail in soft metaphyseal bone is technically challenging because the fracture is not directly visualized and requires adequate closed reduction before nail insertion.[48] In addition, some surgeons are not inclined to place screws across an intramedullary device in the diaphysis, as it may cause a stress riser, while others are concerned about the associated complications such as superficial radial nerve injury and distal radioulnar joint (DRUJ) screw penetration.[4,23]

Our study has several limitations. The use of synthetic bone models limits the generalizability of our results to the clinical setting, and there may be differences in bone quality that variably affect the different plating constructs. Our synthetic model also lacked soft tissues, preventing us from assessing whether the intramedullary nail has greater stabilization secondary to preserved soft tissue integrity, a theoretical benefit of the implant. With regards to force generation, our study assessed only stability and stiffness in the axial plane; we did not account for eccentric or torsional forces likely seen in the postoperative setting. Lastly, our fracture model accounted only for unstable extra-articular fractures. The biomechanical properties of the constructs may change with intra-articular or comminuted fractures.

Despite the limitations, our study provides promising biomechanical results for the use of intramedullary nails. Our study and previous studies demonstrate that the intramedullary nail has the biomechanical properties to maintain anatomic reduction of distal radial fractures when subjected to simulated forces experienced across the fracture site during early postoperative rehabilitation. Although the intramedullary nail did not achieve the same level of stiffness as the volar plate, it performed well and demonstrated the necessary stiffness to maintain adequate reduction in the postoperative rehabilitation setting. Intramedullary nails may be best suited in extra-articular, dorsally displaced distal radius fractures, particularly in patients with compromised soft tissues on the volar aspect of the wrist. Further studies are needed that continue to assess the biomechanical properties, long-term outcomes, and complications of intramedullary nail fixation in distal radius fractures.

Conflicts of Interest
None

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